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Framework for Understanding Global Versus Local Energy Deposition into the Ionosphere and Thermosphere

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The primary objective of this investigation was aimed at understanding how regional and localized heating of the ionosphere and thermosphere can occur and how it affects the structure of the thermosphere, in particular with respect to neutral upwelling and satellite drag. This study both employed data analysis, primarily using DMSP data, and global modeling using the coupled OpenGGCM-CTIM model. We studied the thermospheric response to sheath-enhanced storms and found that an event chain of high solar wind density, soft electron precipitation, and NO cooling may lead to thermosphere contraction and density mispredictions. Using OpenGGCM modeling we found that the soft electron precipitation can profoundly alter the current closure in the ionosphere and change the Joule heating patterns. We re-processed ST-5 and DMSP magnetic field data to show that magnetic perturbations track the passage of co-rotating interaction regions and high-speed solar wind, and that a radial IMF component can enhance a weak southward IMF to lead to sawtooth oscillations. We examined the thermospheric neutral density response to 172 solar wind high-speed streams (HSSs) and the associated stream interfaces during the equinox seasons of 2002–2008 to show that

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"Framework for Understanding Global Versus Local Energy Deposition into the Ionosphere and Thermosphere"

The primary objective of this investigation was aimed at understanding how regional and localized heating of the ionosphere and thermosphere can occur and how it affects the structure of the thermosphere, in particular with respect to neutral upwelling and satellite drag. This study both employed data analysis, primarily using DMSP data, and global modeling using the coupled OpenGGCM-CTIM model.

In the following we highlight the scientific achievements that resulted from this grant.

In Knipp, D. J. et al., (2013), Thermospheric damping response to sheath-enhanced geospace storms, *Geop. Res Lett*., doi:10.1002/grl.50197, we showed evidence that solar wind density enhancements and pressure pulses can lead to intense low-energy particle precipitation and an associated, but unexpected, damping of thermospheric density response. Ground-based indices, used as proxies for thermospheric energy deposition, fail to capture these interactions in forecasting algorithms. Superposed epoch comparison of a group of poorly specified neutral density storms suggests an event-chain of (1) multi-hour, pre-storm solar wind density enhancement, followed by solar wind dynamic pressure pulses that trigger excess low-energy particle flux to the upper atmosphere; (2) enhanced production of thermospheric Nitric Oxide (NO) by precipitating particles and storm heating; (3) NO infrared cooling and damping of the thermosphere; and (4) mis-forecast of neutral density. In the control storms, these features are absent or muted. We discussed the roles of solar wind pre-conditioning and solar cycle dependency in the problem storms. These problem neutral-density storms reveal an element of **"**geo-effectiveness**"** that highlights competition between hydrodynamic aspects of the solar wind and other interplanetary drivers. The implication is that the thermosphere responds in a highly non-linear fashion to a combination of solar wind driving and system preconditioning, and further that knowledge of NO behavior and distribution is a critical component of successfully forecasting neutral density response.

In a follow-up study, Joseph Jensen (Raeder's graduate student) used OpenGGCM simulations to show that the soft electron precipitation indeed alters the conductance profiles, and thus the Joule heating significantly. The precipitation raises the conductance profile, which leads to new current paths, such that current closes at higher altitudes and increases the Joule heating at higher altitudes. We have not yet been able to verify increased thermospheric NO production and the resulting radiative cooling. These results have so far been presented at the 2015 GEM and CEDAR meetings.

In Knipp, D. J., et. (2015), A large-scale view of Space Technology 5 magnetometer

response to solar wind drivers, *Earth and Space Science*, 2, doi:10.1002/2014EA000057, we developed the ability to reprocess space-based magnetometer data into a common data format at a common reference altitude. This is a necessary first step in preparing DMSP magnetometer data for large-scale use in estimating Poynting flux along the satellite track. Reprocessing includes (1) transforming the data into the Modified Apex Coordinate System for projection to a common reference altitude, (2) correcting gain jumps, and (3) validating the results. We can display the averaged magnetic perturbations as a keogram, which allows direct comparison of the full-mission data with the solar wind values and geomagnetic indices. With the data referenced to a common altitude, we find the following: (1) Magnetic perturbations that track the passage of corotating interaction regions and high-speed solar wind; (2) unexpectedly strong dayside perturbations during a solstice magnetospheric sawtooth oscillation interval characterized by a radial interplanetary magnetic field (IMF) component that may have enhanced the accompanying modest southward IMF; and (3) intervals of reduced magnetic perturbations or "calms," associated with periods of slow solar wind, interspersed among variable-length episodic enhancements. These calms are most evident when the IMF is northward or projects with a northward component onto the geomagnetic dipole. The reprocessed DMSP data are in very good agreement with magnetic perturbations from the Space Technology-5 (ST5) spacecraft, which we also map to 110 km. Our methods form the basis for future intermission comparisons of space-based magnetometer data. This work is a natural lead-in for making full use of the extensive archive of DMSP magnetometer data and the eventual utility of data from the AMPERE (or similar) system.

In McGranaghan, R., D. J. Knipp, R. L. McPherron, and L. A. Hunt (2014), Impact of equinoctial high-speed stream structures on thermospheric responses, *Space Weather*, 12, doi:10.1002/2014SW001045, we examined thermospheric neutral density response to 172 solar wind high-speed streams (HSSs) and the associated stream interfaces during the equinox seasons of 2002–2008. HSSs produce prolonged enhancements in satellite drag. We found responses to two drivers: (1) the equinoctial Russell-McPherron effect, which allows the azimuthal component of the interplanetary magnetic field (IMF) to project onto Earth's vertical dipole component, and (2) coronal streamer structures, which are extensions of the Sun's mesoscale magnetic field into space. Events for which the IMF projection is antiparallel to the dipole field are classified as "Effective-E;" otherwise, they are "Ineffective-I." Effective orientations enhance energy deposition and subsequently thermospheric density variations. The IMF polarities preceding and following stream interfaces at Earth produce events that are Effective-Effective-EE, Ineffective-Ineffective-II, Ineffective-Effective-IE, and Effective-Ineffective-EI. These categories are additionally organized according to their coronal source structure: helmet streamers (HS-EI and HS-IE) and pseudo-streamers (PS-EE and PS-II). Approximately 65% of these combinations are HS-EI or HS-IE. The response to HS-IE structures is smoothly varying and long-lived, while the response to PS-EE structures is erratic, short-lived, and modulated by thermospheric preconditioning. We find significant distinguishable responses to these drivers in four geomagnetically sensitive observations: low-energy particle precipitation, proxied Joule heating, nitric oxide flux, and neutral density. Distinct signatures exist in neutral density response that can be anticipated

days in advance based on currently available knowledge of on-disk coronal holes. Further, we show that the HS-IE events produce the largest neutral density disturbances, with $\delta\rho$max,IE exceeding $\delta\rho$max, EI bymore than 30%. This work reports previously unknown associations between structures on the Sun that propagate into the solar wind and further can have counterintuitive effects on thermospheric density response.

In McGranaghan, R., D. J. Knipp, S. C. Solomon, and X. Fang (2015), A fast, parameterized model of upper atmospheric ionization rates, chemistry, and conductivity, *J. Geophys. Res. - Space Physics*, 120, doi:10.1002/2015JA021146, we introduce a parameterized, updated, and extended version of the GLobal AirglOW (GLOW) model, called GLOWfast, that significantly reduces computation time and provides comparable accuracy in upper atmospheric ionization, densities, and conductivity. We extend GLOW capabilities by (1) implementing the nitric oxide empirical model, (2) providing a new model component to calculate height-dependent conductivity profiles from first principles for the 80–200 km region, and (3) reducing computation time. The computational improvement is achieved by replacing the full, two-stream electron transport algorithm with two parameterizations: (1) photoionization (QRJ from Solomon and Qian (2005)) and (2) electron impact ionization (F0810 from Fang et al. (2008, 2010)). We find that GLOWfast accurately reproduces ionization rates, ion and electron densities, and Pedersen and Hall conductivities independent of the background atmospheric state and input solar and auroral activity. Our results suggest that GLOWfast may be even more appropriate for low characteristic energy auroral conditions. We demonstrate in a suite of 3028 case studies that GLOWfast can be used to rapidly calculate the ionization of the upper atmosphere with few limitations on background and input conditions. We support these results through comparisons with electron density profiles from COSMIC.

With Tobiska, W. K., D. Knipp, W. J. Burke, D. Bouwer, J. Bailey, D. Odstrcil, M. P. Hagan, J. Gannon, and B. R. Bowman (2013), The Anemomilos prediction methodology for Dst, *Space Weather*, 11, 490–508, doi:10.1002/swe.20094, we described new capabilities for operational multi-day geomagnetic Disturbance storm time (Dst) index forecasts. We present a data-driven, deterministic algorithm called Anemomilos for for large, medium, and small storms, depending upon transit time to the Earth. This capability is used for operational satellite management and debris avoidance in Low Earth Orbit (LEO). Anemomilos has a 15 min cadence, 1 h time granularity, 144 h prediction window (+6 days), and up to 1 h latency. Comparisons between Anemomilos predicted and measured Dst for every hour over 25 months in three continuous time frames between 2001 (high solar activity), 2005 (low solar activity), and 2012 (rising solar activity) are shown. The Anemomilos operational algorithm is an operational space weather technology breakthrough using solar disk observables to predict geomagnetically effective Dst up to several days at 1 h time granularity. Real-time forecasts are presented at http://sol.spacenvironment.net/~sam_ops/index.html?

In Connor, H. K., E. Zesta, D. M Ober, and J. Raeder (2014) The relation between transpolar potential and reconnection rates during sudden enhancement of solar wind dynamic pressure: OpenGGCM-CTIM results, *J. Geoph. Res*., 119, 3411-3429,

doi:10.1002/2013JA019728, we have shown that steep increases in dynamic pressure cause different effects depending on whether the IMF is northward or southward. In the southward case, both dayside and nightside reconnection increases and contributes to an enhanced polar cap potential. By contrast, when the IMF is northward, dayside reconnection weakens. We also find that the simulation results agree very well with the DMSP observations of cross-polar cap potential and the open-closed boundary.

In Oliveira, D. M. and J. Raeder (2014), Impact angle control of interplanetary shock geoeffectiveness (2014), *J. Geoph. Res.*, 119, 8188-8201, DOI:10.1002/2014JA020275, we used OpenGGCM simulations to investigate which interplanetary shock parameters control the geoeffectiveness of interplanetary shocks the most. Obviously, the shock strength, as measured by shock speed, Mach number, or compression ratio, is important. However, we found that the impact angle, i.e., the angle between the shock normal and the sun-Earth line, is just as important. We also found that the shock impacts induce large amplitude ULF waves (Pc5) in the night side, but not in the day side. Oliveira, D. M., and J. Raeder, Impact angle control of interplanetary shock geoeffectiveness: A statistical study (2015), *J. Geophys. Res.*, 120, 1-11, DOI:10.1002/2015JA021147, followed up on the previous study. A database of 461 IP shocks, spanning the interval 1995 – 2013, was assembled, and for each shock a Rankine-Hugoniot analysis was performed to obtain shock normal and strength. As a measure for geoeffectiveness we used the SuperMAG SML and SME indices. The statistical analysis confirmed the simulation results, namely that geoeffectiveness is ordered by shock strength and impact angle. Surprisingly, geoeffectiveness correlates better with impact angle than with shock speed. We also attempted to derive a correlation with auroral energy input, but unfortunately that paper was rejected (but is posted on arxiv: Oliveira, D. M., J. Raeder, B. T. Tsurutani, and J. W. Gjerlov, Effects of interplanetary shock inclinations on auroral power
intensity, http://arxiv.org/pdf/1507.02027.pdf). We still plan to publish an improved version of this paper.

Submitted:

With Rastatter, L., J. S. Shim, M. M. Kuznetsova, L. M. Kilcommons, D. J. Knipp, M. Codrescu, T. Fuller-Rowell, B. Emery, D. R. Weimer, R. Cosgrove, M. Wiltberger, J. Raeder, W. Li, G. Toth, D. Welling, GEM-CEDAR challenge: Poynting flux at DMSP and modeled Joule heat, submitted to *Space Weather*, in review, 2015, we contributed DMSP Poyting flux estimates for the GEM-CEDAR Challenge, in which multiple models of the ionosphere were run and electrodynamic parameters were used to compute Joule heat which can be correlated to Poynting flux deposition from DMSP satellite measurements assuming that electromagnetic energy gets dissipated locally. Six events of varying geomagnetic activity were selected for the study and time series and orbit-integrated values were compared. Coupled magnetosphere-ionosphere models and stand-alone models of the ionosphere yield mixed results with some models consistently overestimating Joule heat and some models estimating much smaller Joule heat compared to Poynting flux observations for many (but not all) events. We find that modeled peak

and integrated Joule heat values are scattered over a wide range compared for all types of models which shows that the calculation of Joule heat using large-scale electromagnetic fields cannot properly track the Poynting flux as obtained from in situ satellite observations. In general, models were generating patterns that may resemble the observed Poynting flux but magnitudes were often different by a factor of two or three in either direction (stronger or weaker), as were the integrated values over each auroral pass. No correlation could be found in the timing error between peak modeled Joule heat and peak observed Poynting fluxes with respect to storm phase or storm intensity for any of the [2]models.

1.

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Abstract

The primary objective of this investigation was aimed at understanding how regional and localized heating of the ionosphere and thermosphere can occur and how it affects the structure of the thermosphere, in particular with respect to neutral upwelling and satellite drag. This study both employed data analysis, primarily using DMSP data, and global modeling using the coupled OpenGGCM-CTIM model. We studied the thermospheric response to sheath-enhanced storms and found that an event chain of high solar wind density, soft electron precipitation, and NO cooling may lead to thermosphere contraction and density mispredictions. Using OpenGGCM modeling we found that the soft electron precipitation can profoundly alter the current closure in the ionosphere and change the Joule heating patterns. We re-processed ST-5 and DMSP magnetic field data to show that magnetic perturbations track the passage of co-rotating interaction regions and high-speed solar wind, and that a radial IMF component can enhance a weak southward IMF to lead to sawtooth oscillations. We examined the thermospheric neutral density response to 172 solar wind high-speed streams (HSSs) and the associated stream interfaces during the equinox seasons of 2002–2008 to show that HSSs produce prolonged enhancements in satellite drag. We found that distinct signatures exist in neutral density response that can be anticipated days in advance based on currently available knowledge of on-disk coronal holes. We co-developed capabilities for operational multi-

day geomagnetic Disturbance storm time (Dst) index forecasts, i.e., a data-driven, deterministic algorithm called Anemomilos for large, medium, and small storms, depending upon transit time to the Earth. Using global modeling we showed that steep increases in dynamic pressure cause different effects depending on whether the IMF is northward or southward. Also from modeling we deduced that the impact angle by which interplanetary (IP) shocks hit the magnetosphere is at least as important for their geoeffectiveness as the shock strength. We confirmed this result wit a statistical study of 461 IP shocks spanning more than a solar cycle. We collaborated with CCMC on the GEM-CEDAR challenge: "Poynting flux at DMSP and modeled Joule heat," which is still ongoing.

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Archival Publications (published) during reporting period:

Connor H. J., E. Zesta, D. M. Ober, and J. Raeder (2014),
The relation between transpolar potential and reconnection rates during
sudden enhancement of solar wind dynamic pressure: OpenGGCM-CTIM results,
J. Geoph. Res., 119, 3411 - 3429, DOI:10.1002/2013JA019728

Knipp, D., L. Kilcommons, L. Hunt, M. Mlynczak, V. Pilipenko, B. Bowman, Y. Deng, and K. Drake (2013),
Thermospheric damping response to sheath-enhanced geospace storms,
Geophys. Res. Lett., 40, 1263–1267, doi:10.1002/grl.50197.

Knipp, D. J., L. M. Kilcommons, J. Gjerloev, R. J. Redmon, J. Slavin, and G. Le (2015),
A large-scale view of Space Technology 5 magnetometer response to solar wind drivers,
Earth and Space Science, 2, doi:10.1002/2014EA000057.

McGranaghan, R., D. J. Knipp, R. L. McPherron, and L. A. Hunt (2014),
Impact of equinoctial high-speed stream structures on thermospheric responses,
Space Weather, 12,doi:10.1002/2014SW001045.

McGranaghan, R., D. J. Knipp, S. C. Solomon, and X. Fang (2015),
A fast, parameterized model of upper atmospheric ionization rates, chemistry, and conductivity,
J. Geophys. Res. Space Physics, 120, doi:10.1002/2015JA021146.

Oliveira, D. M., and J. Raeder (2014),
Impact angle control of interplanetary shock geoeffectiveness,
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Tobiska, W. K., D. Knipp, W. J. Burke, D. Bouwer, J. Bailey, D. Odstrcil, M. P. Hagan, J. Gannon, and B. R. Bowman (2013), The Anemomilos prediction methodology for Dst, Space Weather, 11, 490–508, doi:10.1002/swe.20094.

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